

PERFORMANCE EVALUATION OF PHASE CHANGE MECHANISM (PCM) BALL – INTEGRATED CONCRETE: STRENGTH AND THERMAL REGULATION

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Abstract - The construction industry consumes a large amount of energy, especially for heating and cooling buildings, which contributes to greenhouse gas emissions. To improve energy efficiency, this study explores the use of Phase Change Materials (PCMs) in concrete. PCMs can absorb heat when temperatures rise and release it when temperatures drop, helping to maintain stable indoor conditions. In this research, paraffin wax is used as the PCM and is enclosed inside small spherical balls to prevent leakage, then embedded into concrete cubes. Each cube contains two PCM balls and is tested for compressive strength, ultrasonic pulse velocity (UPV), and thermal performance, with results compared to normal concrete. The findings show that adding PCM balls slightly reduces the concrete's strength due to weaker bonding and small voids, but the strength still remains within acceptable limits. At the same time, the thermal performance improves significantly, as the PCM helps delay temperature rise and retain heat for longer periods. This means buildings made with such concrete could require less energy for heating and cooling. Overall, although there is a small reduction in strength, the improved thermal efficiency and durability make PCM-integrated concrete a promising and sustainable construction material.

Key Words: Phase Change Materials (PCM), PCM concrete, paraffin wax, thermal energy storage, sustainable construction, energy efficiency, compressive strength, ultrasonic pulse velocity (UPV), thermal regulation, encapsulation technique

1. INTRODUCTION

This section introduces the study. Modern construction requires both structural safety and energy efficiency, as a large portion of building energy is used for heating and cooling. Therefore, materials that can regulate indoor temperature are increasingly important. Phase Change Materials (PCMs) are effective for thermal energy storage because they absorb and release heat within a narrow temperature range, helping maintain stable conditions. Concrete is widely used due to its strength and durability, but it has poor thermal performance, leading to higher energy consumption. To improve this, PCMs such as paraffin wax can be incorporated into concrete. However, direct

mixing may cause leakage, reduced strength, and durability issues.

To address these challenges, this study uses a macro-encapsulation method, where PCM is enclosed in spherical balls and embedded into concrete. This approach reduces leakage and limits the impact on mechanical properties. The study aims to evaluate compressive strength and thermal performance of PCM-integrated concrete, highlighting its potential for energy-efficient and sustainable construction.

1. LITERATURE REVIEW

Research on Phase Change Materials (PCM) in concrete shows a clear balance between improved thermal performance and reduced mechanical strength. Studies consistently report that PCM enhances thermal energy storage by absorbing and releasing heat, helping regulate temperature in buildings. However, this benefit often comes with drawbacks such as reduced compressive strength, increased porosity, and potential durability concerns due to weak bonding between PCM and the cement matrix.

A 2022 review highlighted that PCM improves thermal storage regardless of the incorporation method, but strength loss remains a key challenge. Macro-encapsulation, especially non-contact methods, is considered more effective as it minimizes direct interaction between PCM and concrete, preserving structural integrity. One notable approach is the use of hollow steel balls filled with PCM, which offer better containment and thermal conductivity. Dong et al. demonstrated that such systems provide high latent heat capacity (around 200.5 J/g) with minimal leakage even after repeated thermal cycles. Their results also showed that PCM-integrated concrete can reduce indoor peak temperatures by 25–33% and delay heat transfer.

Despite these advantages, increasing PCM content leads to a reduction in compressive strength. For example, strength decreased progressively with higher PCM replacement levels, mainly due to weak bonding between smooth PCM surfaces and the cement matrix. However, even the lowest strength values remained within acceptable structural limits, indicating practical usability.

Several other studies support these findings. Adesina (2020) and Sharma et al. (2022) emphasized improved thermal efficiency and reduced energy demand but noted strength and durability concerns. Zhang et al. (2013) and Wei et al. (2017) highlighted the importance of proper encapsulation to prevent leakage and improve durability. Sakulich et al. (2012) and Memon et al. (2015) reported better thermal regulation but reduced strength due to lower density and weak bonding. Pilehvar et al. (2017) found microencapsulation effective but costly, while Feno Llera et al. (2013) observed reduced workability in fresh concrete. More

recent work by Wang et al. (2026) suggests that adding fibres can help recover some strength, though it increases system complexity.

Overall, these studies confirm that PCM-integrated concrete offers significant thermal benefits and energy savings, but careful design is required to balance thermal performance with structural strength.

Table 1: Summary of Literature Review on PCM Integrated Concrete

S. No.	Researcher(s)	Focus Area	Key Findings	Research Gap
1	Adesina (2020)	Review of PCM in concrete	Improves thermal storage but reduces strength	Lacks experimental validation
2	Sharma et al. (2022)	PCM in sustainable buildings	Reduces energy consumption	Durability issues
3	Zhang et al. (2013)	PCM in cement mortar	Improved thermal storage	Leakage issues
4	Sakulich et al. (2012)	PCM in composites	Better thermal regulation	Reduced strength
5	Pilehvar et al. (2017)	Micro-encapsulated PCM	Improved stability	High cost
6	Wei et al. (2017)	Durability study	Improved durability	Complex process
7	Memon et al. (2015)	Macro-encapsulation	Better insulation	Lower strength
8	Feno Llera et al. (2013)	PCM in SCC	Improved inertia	Reduced workability
9	Wang et al. (2026)	Fiber PCM concrete	Improved strength	Complex design

2. METHODOLOGY

The study follows an experimental approach including material selection, PCM encapsulation, concrete casting, curing, and testing. Paraffin octadecane is used as the Phase Change Material (PCM) because it is suitable for building temperature regulation. The PCM is filled into hollow steel balls using a vacuum process and then sealed with epoxy to prevent leakage. These PCM-filled balls are used as partial replacement of coarse aggregate in concrete.

Concrete mixes are prepared with different replacement levels of PCM balls (0%, 25%, 50%, 75%, and 100%) using M25 grade concrete. A constant water-cement ratio is maintained, and a superplasticizer is added to improve workability. The PCM balls are added at the final stage of mixing to avoid damage. Concrete cubes of size 150 mm × 150 mm × 150 mm are cast, each containing two PCM balls placed evenly.

The specimens are cured in water for 7, 14, and 28 days. Tests conducted include compressive strength, ultrasonic pulse velocity (UPV), and thermal performance using infrared temperature measurements. These tests are used to evaluate both the strength and thermal behavior of PCM-integrated concrete for possible use in energy-efficient buildings.

3. System Architecture of Ball-Integrated Concrete

The system of ball-integrated phase change concrete works in four main steps: PCM selection, concrete preparation, thermal regulation, and strength checking.

First, a suitable Phase Change Material (PCM) is selected and filled into hollow steel balls. These balls prevent leakage and help transfer heat efficiently.

Second, the PCM-filled balls are added into concrete by partially replacing coarse aggregate. During high temperature, the PCM absorbs heat and melts, reducing temperature rise. When temperature drops, it solidifies and releases heat, helping maintain stable temperature.

Third, the system improves thermal performance by reducing temperature peaks and fluctuations, which helps in energy savings for buildings.

Finally, the strength of concrete is tested. Since steel balls reduce bonding with cement, compressive strength decreases as more PCM balls are added. Therefore, a proper balance is needed between strength and thermal benefits.

Overall, this system improves thermal comfort and energy efficiency while maintaining usable structural strength.

4. Results and Evaluation

The results of this study show that ball-integrated Phase Change Material (PCM) concrete significantly improves thermal performance. The inclusion of PCM-filled steel balls helps in reducing indoor temperature and delaying the peak heat time compared to conventional concrete. In experimental studies, the peak indoor temperature was observed to drop considerably when PCM panels were used, confirming that the latent heat storage capacity of PCM effectively absorbs excess heat during high-temperature conditions and releases it slowly when the temperature decreases. This process helps in maintaining a more stable and comfortable indoor environment.

The thermal performance improves as the amount of PCM balls in the concrete increases. This is because a higher PCM content allows more heat energy to be stored and released during phase change, which reduces sudden temperature fluctuations. As a result, PCM-integrated concrete can reduce the dependence on artificial cooling systems and improve overall energy efficiency in buildings.

However, the mechanical performance shows a declining trend with increasing PCM content. The compressive strength of concrete decreases as more PCM balls replace the natural coarse aggregate. This reduction in strength is mainly due to the weak bonding between the smooth steel surface of the PCM balls and the cement matrix, which creates interfacial gaps and reduces load-bearing capacity. Despite this reduction, lower and moderate replacement levels still maintain acceptable structural strength.

Overall, the results clearly indicate a trade-off between thermal efficiency and mechanical strength. While higher PCM content improves temperature regulation, it negatively affects strength. Therefore, an optimized replacement level is necessary to achieve a balance between both properties. Moderate use of PCM balls provides the best performance by offering significant thermal benefits while maintaining sufficient structural integrity.

CONCLUSIONS

This study concludes that ball-integrated Phase Change Material (PCM) concrete is an effective solution for improving thermal performance in buildings while maintaining acceptable structural strength. The use of PCM-filled steel balls helps control indoor temperature by absorbing heat during high temperatures and releasing it during cooling periods, which reduces peak temperatures and improves thermal comfort.

Results show that thermal efficiency increases with higher PCM content. However, compressive strength decreases due to weak bonding between the steel balls and the cement matrix. Despite this reduction, the concrete still performs

adequately for non-structural and semi-structural applications.

A balanced replacement level of about 25–50% coarse aggregate with PCM balls is found to be optimal, providing a good compromise between strength and thermal benefits.

Overall, this material shows strong potential for sustainable construction, especially in building elements like walls and panels where thermal regulation is important. It helps reduce energy consumption and supports energy-efficient building design.

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